P and T odd electromagnetic moments of deuteron in chiral limit

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Abstract

P odd anapole moment of the deuteron is found in the chiral limit, $m_\pi \to 0$. The contact current generated by the P odd pion exchange does not contribute to the deuteron anapole. Being combined with usual radiative corrections to the weak electron – deuteron interaction, our calculation results in a sufficiently accurate theoretical prediction for the corresponding effective constant C_{2d}. The experimental measurement of this constant would give valuable information on the P odd πNN constant and on the s-quark content of nucleons. We calculate also in the same limit $m_\pi \to 0$ the deuteron P odd and T odd multipoles: electric dipole moment and magnetic quadrupole moment.

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Dedicated to the memory of Slava Ryndin

1 Introduction

The investigations of nuclear parity violation, both theoretical and experimental, have already a long history. New light on this problem is shed by observation of the nuclear anapole moment (AM) of ^{133}Cs in atomic experiment [1]. The result of this experiment is in a reasonable quantitative agreement with the theoretical predictions, starting with [2, 3], if the so-called "best values" [4] are chosen for the parameters of P odd nuclear forces.

The AM is a rather peculiar multipole in the following sense (for a more detailed discussion see, for instance, [5]). The interaction of a charged probe particle with an anapole moment is of a contact nature. Therefore, for instance, the interaction of the electron with the nucleon AM, being on the order of αG, cannot be distinguished in general case from other electromagnetic radiative corrections to the weak electron-nucleon interaction due to the neutral currents. And in a gauge theory of electroweak interactions only the total scattering amplitude, i.e., the sum of all diagrams on the order of αG, is gauge-invariant, independent of the gauge choice for the Green's functions of heavy vector bosons (here α is the fine-structure constant, G is the Fermi weak interaction constant). No wonder that, generally speaking, the AM of an elementary particle or a nucleus is not gauge-invariant, i.e., physically well-defined, quantity. However, there is a special case where the anapole moment has a real independent physical meaning. In heavy nuclei, of course ^{133}Cs included, the AM is enhanced $\sim A^{2/3}$ [3] (A is the atomic number), as distinct from common radiative corrections. By the way, it means that there is an intrinsic limit for the relative accuracy, $\sim A^{-2/3}$, with which the AM of a heavy nucleus can be defined at all. For ^{133}Cs this limiting accuracy is about 4%.

There is one more object, the deuteron, whose anapole moment could make sense for a sufficiently large P odd πNN constant [2]. The deuteron is a loosely bound system of a relatively simple structure. Therefore, there are all the reasons to believe that its AM is induced mainly by the P odd π-meson exchange, pion being the lightest possible mediator of the nucleon-nucleon weak interaction. The problem of the deuteron AM was discussed phenomenologically in [2,6-8]. In the present work the deuteron AM, as induced by the P odd π-meson exchange, is explicitly expressed through the P odd πNN coupling constant. The same problem was considered in recent paper [9]. The result of the original version of [9] was much smaller than ours because a leading contribution, that of the isovector magnetic moment of the nucleon, was omitted in it. After acquaintance with the preprint of

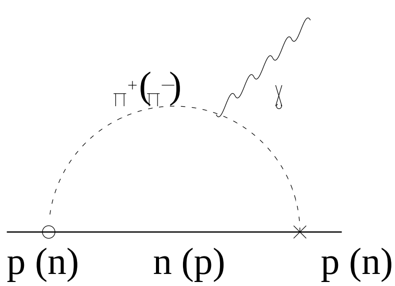
the present work, the authors of [9] corrected their result (see their revised preprint [9], Section VI. Erratum and Addendum). On the other hand, under the influence of [9], we have refined our own calculations with the results presented below.

The obtained result for the deuteron AM is singular as $1/m_\pi$ in the limit $m_\pi \to 0$ (of course, when going over to this limit, one should keep the deuteron radius larger than the Compton wave length of the pion). Being combined with the radiative corrections to the weak electron – deuteron scattering amplitude [10], which are regular in m_π, our calculations result in a sufficiently accurate value for the corresponding effective constant C_{2d}.

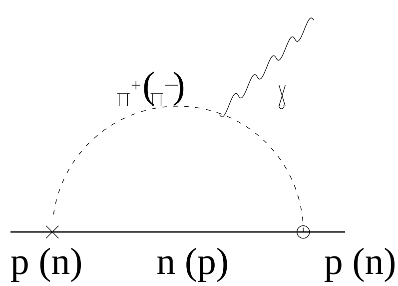
We also calculate here the P odd and T odd electromagnetic moments of the deuteron.

2 The deuteron anapole moment

It is convenient to start the discussion with the nucleon AM in the chiral limit. It was shown in 1980 by A.I. Vainshtein and one of the authors (I.Kh.) to be given in this limit by the diagrams 1 and 2. The circle on the nucleon lines



F i g . 1



F i g . 2

refers to the usual strong interaction πNN vertex (coupling constant $g\sqrt{2}$), the cross describes the P odd weak πNN interaction (coupling constant $\bar{g}\sqrt{2}$). The result for the nucleon AM is

$$\mathbf{a}_N = \mathbf{a}_p = \mathbf{a}_n = -\frac{eg\bar{g}}{12m_p m_\pi}\left(1 - \frac{6}{\pi}\frac{m_\pi}{m_p}\ln\frac{m_p}{m_\pi}\right)\boldsymbol{\sigma}. \quad (1)$$

The diagrams discussed lead to the same result for a proton and neutron since under the permutation $p \leftrightarrow n$ the strong coupling constant g does not change, and the weak one $\bar{g}$ changes sign together with the charge e of the π-meson (we assume $e > 0$, exact definitions of the strong and weak interaction Lagrangians and coupling constants g and $\bar{g}$ are given below). Being the only contribution to the nucleon AM, which is singular in m_π, the result (1) is gauge-invariant. In this respect, it has a physical meaning.

Unfortunately, in spite of the singularity in m_π, the corresponding contribution to the electron-nucleon scattering amplitude is small numerically as compared to other radiative corrections to the weak scattering amplitude. Indeed, the radiative corrections to the effective constants $C_{2p,n}$ of the proton and neutron axial neutral-current operators $G/\sqrt{2}\,C_{2p,n}\boldsymbol{\sigma}_{p,n}$ are [10]

$$C^r_{2p} \;=\; 0.032 \pm 0.030\,, \quad C^r_{2n} \;=\; -0.018 \pm 0.030\,. \tag{2}$$

In the same units $G/\sqrt{2}$, the effective axial constants induced by the electromagnetic interaction with the proton and neutron anapole moments (1), is

$$C^a_{p,n} \;=\; -\,\alpha a_N\,(|e|G/\sqrt{2})^{-1} \;=\; 0.07 \times 10^5 \bar{g}.$$

At the "best value" $\bar{g} = 3.3 \times 10^{-7}$ (strongly supported by the experimental result for the ^{133}Cs anapole moment) we obtain

$$C^a_{p,n} \;=\; 0.002. \tag{3}$$

With this value being much less than both central points and error bars in (2), the notion of the nucleon AM practically has no physical meaning. This is why the result (1) was never published by the authors. It is quoted in book [5] (without the logarithmic term) just as a theoretical curiosity. The logarithmic term in the nucleon AM is discussed in [11].

However, the situation with the deuteron AM is quite different. Not only the proton and neutron AMs add up here. The isovector part of the radiative corrections is much smaller than the individual contributions C^r_{2p} and C^r_{2n}, and is calculated with much better accuracy [10]:

$$C^r_{2d} \;=\; C^r_{2p} + C^r_{2n} \;=\; 0.014 \pm 0.003\,. \tag{4}$$

Moreover, there is the already mentioned, qualitatively new contribution, due to the isovector magnetic moment of the nucleon, which dominates numerically the deuteron AM. Thus a_d acquires a real physical meaning.

Let us go over now to the problem itself. The Lagrangians of the strong πNN interaction and of the weak P odd one, L_s and L_w, respectively, are well-known:

$$L_s \;=\; g\,[\,\sqrt{2}\,(\overline{p}i\gamma_5 n\,\pi^+ + \overline{n}i\gamma_5 p\,\pi^-) \,+ (\,\overline{p}i\gamma_5 p - \overline{n}i\gamma_5 n)\,\pi^0]; \tag{5}$$

$$L_w \;=\; \bar{g}\,\sqrt{2}\,i\,(\,\overline{p}n\,\pi^+ - \overline{n}p\,\pi^-). \tag{6}$$

Our convention for γ_5 is

$$\gamma_5 = \begin{pmatrix} 0 & -I \\ -I & 0 \end{pmatrix}; \tag{7}$$

the relation between our P odd πNN constant $\bar{g}$ and the common one $h^{(1)}_{\pi NN}$ is $\bar{g}\sqrt{2} = h^{(1)}_{\pi NN}$.

The effective nonrelativistic Hamiltonian of the P odd nucleon-nucleon interaction due to the pion exchange is in the momentum representation

$$V(\mathbf{q}) \;=\; \frac{2g\bar{g}}{m_p}\,\frac{(\mathbf{I}\mathbf{q})}{m_\pi^2+\mathbf{q}^2}(N_1^\dagger\tau_{1-}N_1)\,(N_2^\dagger\tau_{2+}N_2). \tag{8}$$

Here

$$\mathbf{I}=\frac{1}{2}(\boldsymbol{\sigma}_p+\boldsymbol{\sigma}_n)$$

is the deuteron spin, $\mathbf{q}=\mathbf{p}_1'-\mathbf{p}_1=-(\mathbf{p}_2'-\mathbf{p}_2)=\mathbf{p}_n'-\mathbf{p}_p=-(\mathbf{p}_p'-\mathbf{p}_n)$. Let us note that the P odd interaction (8) which interchanges the proton and neutron, when applied to the initial state $a_p^\dagger(\mathbf{r}_1)a_n^\dagger(\mathbf{r}_2)|0\rangle$ transforms it into $a_n^\dagger(\mathbf{r}_1)a_p^\dagger(\mathbf{r}_2)|0\rangle=-a_p^\dagger(\mathbf{r}_2)a_n^\dagger(\mathbf{r}_1)|0\rangle$. On the other hand, the coordinate wave function of the admixed $^3P_1$ state is proportional to the relative coordinate $\mathbf{r}$, which we define as $\mathbf{r}_p-\mathbf{r}_n$. Therefore, it also changes sign under the permutation $p\leftrightarrow n$. Thus, for the deuteron the P odd potential can be written in the coordinate representation as a simple function of $\mathbf{r}=\mathbf{r}_p-\mathbf{r}_n$ without any indication of the isotopic variables:

$$V(\mathbf{r}) \;=\; \frac{g\bar{g}}{2\pi m_p}\,(-i\mathbf{I}\cdot\boldsymbol{\nabla})\,\frac{\exp\,(-m_\pi r)}{r} \tag{9}$$

The above expressions are rather standard. As standard is our sign convention for the coupling constants: $g=13.45$, and $\bar{g}>0$ for the range of values discussed in [4].

The discussed P odd interaction V generates a contact current $\mathbf{j}^c$. To obtain the explicit expression for it, we have to consider V in the presence of the electromagnetic field. Its including modifies the proton momentum: $\mathbf{p}\to\mathbf{p}-e\mathbf{A}$, which results in the shift $\mathbf{q}\to\mathbf{q}+e\mathbf{A}$ in the interaction (8). Then in the momentum representation the contact current is

$$\begin{aligned}\mathbf{j}^c(\mathbf{q}) \;&=\; -\,\frac{\partial V(\mathbf{q})}{\partial\mathbf{A}} \;=\; -\,\frac{\partial}{\partial\mathbf{A}}\,\frac{2g\bar{g}}{m_p}\,\frac{\mathbf{I}(\mathbf{q}+e\mathbf{A})}{m_\pi^2+(\mathbf{q}+e\mathbf{A})^2}\\ &=\; -\,\frac{2eg\bar{g}}{m_p}\,\left\{\frac{\mathbf{I}}{m_\pi^2+\mathbf{q}^2}\;-\;\frac{2\mathbf{q}(\mathbf{I}\mathbf{q})}{(m_\pi^2+\mathbf{q}^2)^2}\right\}.\end{aligned} \tag{10}$$

In the last expression we have neglected the dependence of the contact current on $\mathbf{A}$. In the coordinate representation it equals

$$\mathbf{j}^c(\mathbf{r}) \;=\; \frac{eg\bar{g}}{2\pi m_p}\,\mathbf{r}(\mathbf{I}\boldsymbol{\nabla})\frac{e^{-m_\pi r}}{r}\,. \tag{11}$$

Let us derive at first a general structure of the deuteron AM generated by a P odd np interaction, assuming only that the deuteron is a pure $^3S_1$ state, bound by a spherically symmetric potential. We follow here essentially the

line of reasoning applied in [2] (see also book [5]) to the problem of a single proton in a spherically symmetric potential. In this case the formula for the AM operator is [2]

$$\mathbf{a} = \frac{\pi e}{m_p} \{\mu_p \mathbf{r} \times \boldsymbol{\sigma} - \frac{i}{3} [\mathbf{l}^2, \mathbf{r}]\} + \frac{2\pi}{3} \mathbf{r} \times [\mathbf{r} \times \mathbf{j}^c], \tag{12}$$

with the proton magnetic moment $\mu_p = 2.79$. In the case of the deuteron this formula generalizes to

$$\mathbf{a}_d = \frac{\pi e}{2m_p} \{\mathbf{r} \times (\mu_p \boldsymbol{\sigma}_p - \mu_n \boldsymbol{\sigma}_n) - \frac{i}{6} [\mathbf{l}^2, \mathbf{r}]\} + \frac{\pi}{6} \mathbf{r} \times [\mathbf{r} \times \mathbf{j}^c], \tag{13}$$

$\mu_n = -1.91$ is the neutron magnetic moment. Both AM operators (12) and (13) are orthogonal to $\mathbf{r}$ (neither of them commutes with $\mathbf{r}$, so the orthogonality means here that $\mathbf{ar} + \mathbf{ra} = 0$). Therefore, the contact current (11) generated by the P odd pion exchange and directed along $\mathbf{r}$, does not contribute to the nuclear AM.

Let us present now the wave function of the deuteron $^3S_1$ state as $\psi_0(r)\chi$, where χ is the spin wave function for $I = 1$ (we neglect here and below a small $^3D_1$ admixture in the deuteron). If the P odd interaction conserves the total spin $\mathbf{I}$ of the deuteron, the $^3P_1$ state admixed by it can be written as $i(\mathbf{Ir}/r)\psi_1(r)$ (both radial wave functions, $\psi_0(r)$ and $\psi_1(r)$, are spherically symmetric). Simple calculations demonstrate that the deuteron AM, as induced by the operator (13), is in the absence of the contact contribution

$$\mathbf{a}_d = \frac{\pi e}{3m_p} \left(\mu_p - \mu_n - \frac{1}{3}\right) \int d\mathbf{r} r \psi_0(r) \psi_1(r). \tag{14}$$

So, under the assumptions made, the deuteron AM should depend on the universal combination $(\mu_p - \mu_n - 1/3)$.

We confine mainly in our calculation to the naïve zero-range approximation (ZRA) for the deuteron wave function:

$$\psi_0^{(0)}(r) = \sqrt{\frac{\kappa}{2\pi}} \frac{\exp(-\kappa r)}{r}. \tag{15}$$

Here $\kappa = \sqrt{m_p \varepsilon}$; $\varepsilon = 2.23$ MeV is the deuteron binding energy.

The P odd correction to the deuteron wave function due to $V(\mathbf{r})$ will be found in the common stationary perturbation theory. In the same ZRA the admixed $^3P_1$ states of the continuous spectrum are free. Moreover, we can choose plane waves as the intermediate states since the perturbation $V(\mathbf{r})$ selects by itself the P-state from the plane wave. Thus obtained first-order correction to the wave function is

$$\psi_1(\mathbf{r}) = \int \frac{d\mathbf{k}}{(2\pi)^3} \frac{e^{i\mathbf{kr}}}{-\varepsilon - k^2/m_p} \int d\mathbf{r}' \, e^{-i\mathbf{kr}'} V(\mathbf{r}') \, \psi_0(r'). \tag{16}$$

Rather lengthy calculation leads to the following expression for the matrix element of the radius-vector:

$$\int d\mathbf{r}\psi_0(r)\mathbf{r}\psi_1(\mathbf{r}) \;=\; -\,\frac{i\mathbf{I}g\bar{g}}{6\pi m_\pi}\,\frac{1+\xi}{(1+2\xi)^2}, \tag{17}$$

where $\xi = \kappa/m_\pi \;=\; 0.32$. With this matrix element and the operator (13) one obtains easily the following result for the deuteron AM:

$$\mathbf{a}_d^{(0)} \;=\; -\,\frac{eg\bar{g}}{6m_p m_\pi}\,\frac{1+\xi}{(1+2\xi)^2}\,\left(\mu_p - \mu_n - \frac{1}{3}\right)\mathbf{I}, \tag{18}$$

in accordance with the general formula (14). Our overall factor at the structure $(\mu_p - \mu_n - 1/3)$ is the same as that at $(\mu_p - \mu_n)$ in the revised version of [9]. However, the corresponding total result obtained in [9], even in it revised version, is not proportional to the universal combination $(\mu_p - \mu_n - 1/3)$.

In fact, the range $1/m_\pi$ of the P odd interaction (9) is quite comparable to the range of the usual nuclear forces. Therefore, it is, strictly speaking, inconsistent to use the zero-range approximation for calculating effects induced by the perturbation $V(\mathbf{r})$. Still, numerical estimates made with a model deuteron wave function which has somewhat more realistic properties, indicate that the error introduced by using the ZRA does not exceed 20%. As to other sources of P violation, different from the pion exchange, there are no reasons to expect that in the case of deuteron their neglect creates a serious error if the P odd πNN coupling constant $\bar{g}$ is at least comparable to its "best value".

It looks reasonable to combine the potential contribution (18) with the additive contribution of the nucleon anapole moments, which according to (1) is

$$\mathbf{a}_d^N \;=\; \mathbf{a}_p \,+\, \mathbf{a}_n \;=\; -\,\frac{eg\bar{g}}{6m_p m_\pi}\left(1 - \frac{6}{\pi}\,\frac{m_\pi}{m_p}\ln\frac{m_p}{m_\pi}\right)\mathbf{I}. \tag{19}$$

In this way we arrive at the final result for the deuteron AM in the chiral limit:

$$\mathbf{a}_d \;=\; -\,\frac{eg\bar{g}}{6m_p m_\pi}\left[0.49\,(\mu_p - \mu_n - \frac{1}{3}) \,+\, 0.46\right]\mathbf{I} \;=\; -2.60\,\frac{eg\bar{g}}{6m_p m_\pi}\,\mathbf{I}\,. \tag{20}$$

This result includes all contributions to the P odd amplitude of ed-scattering, which are singular in m_π, and thus is gauge-invariant, independent of the gauge choice for the Green's functions of heavy vector bosons.

Finally, let us compare the contribution of (20) to the P odd ed scattering amplitude which is due to the usual radiative corrections, nonsingular in m_π. For the deuteron the axial operator looks as follows:

$$\frac{G}{\sqrt{2}}\,C_{2d}\,\mathbf{I}\,.$$

The contributions to the isoscalar axial constant C_{2d} originate from the anapole moment, from usual radiative corrections nonsingular in m_π, and from the admixture of strange quarks in nucleons [13]. The magnitude of the s-quarks contribution is extremely interesting, but highly uncertain. As to the usual radiative corrections, their contribution to this constant is found in [10] with good accuracy (see (4): $C^r_{2d} = 0.014 \pm 0.003$. In the same units $G/\sqrt{2}$ the effective axial constant induced by the electromagnetic interaction with the deuteron AM (20) is

$$C^a_{2d} = \alpha a_d (eG/\sqrt{2})^{-1} = 0.44 \times 10^5 \bar{g}. \tag{21}$$

At the "best value" $\bar{g} = 3.3 \times 10^{-7}$ (strongly supported by the experimental result for the ^{133}Cs anapole moment) we obtain

$$C^a_{2d} = 0.014 \pm 0.003. \tag{22}$$

We use here the above estimate of 20% for the accuracy of our calculation (for given $\bar{g}$). The numbers in (4) and (22) are quite comparable, and taken together result in the following value of the total effective constant:

$$C_{2d} = C^r_{2d} + C^a_{2d} = 0.028 \pm 0.005. \tag{23}$$

We are fully aware of the extreme difficulty of the experimental measurement of the constant C_{2d}. However, with such a good accuracy of the theoretical prediction (23), this experiment becomes a source of the valuable information on the P odd πNN constant and on the s-quark content of nucleons. As it was 15 years ago, now again "C_{2d} seems to be the most interesting parity-violating parameter accessible to atomic-physics experiments" [10], although by rather different reasons.

Of course, if necessary the accuracy of our prediction (22) can be improved by using a more detailed and realistic description of the deuteron. On the other hand, the accuracy of radiative corrections (4) can be also improved, at least by using much more precise modern experimental values of the parameters of the electroweak theory.

3 The deuteron P odd, T odd moments

The problem of the deuteron P odd, T odd multipoles: electric dipole, magnetic quadrupole, and the so-called Schiff moment, was treated phenomenologically in [14]. Now we will calculate the electric dipole and magnetic quadrupole moments within the approach applied above to the anapole. As to the Schiff moment, strong cancellations occur when calculating its value for the deuteron [14]. Therefore, one cannot expect reasonable accuracy for

it with our ZRA deuteron wave function, and we will not consider here this problem.

As distinct from the P odd, T even interaction, there are three independent P odd, T odd effective πNN Lagrangians. They are conveniently classified by their isotopic properties:

$$\Delta T = 0. \quad L_0 \;=\; g_0\,[\,\sqrt{2}\,(\overline{p}n\,\pi^+ + \overline{n}p\,\pi^-)\; + (\,\overline{p}p - \overline{n}n)\,\pi^0]; \tag{24}$$

$$|\Delta T| = 1. \quad L_1 \;=\; g_1\,\bar{N}N\,\pi^0 \;=\; g_1\,(\,\overline{p}p\,+\,\overline{n}n\,)\,\pi^0); \tag{25}$$

$$\begin{aligned} |\Delta T| = 2. \quad L_2 \;&=\; g_2\,(\,\bar{N}\boldsymbol{\tau}N\,\boldsymbol{\pi}\;-\;3\bar{N}\tau^3N\,\pi^0\,) \\ &=\; g_2\,[\,\sqrt{2}\,(\overline{p}n\,\pi^+ + \overline{n}p\,\pi^-) - 2\,(\,\overline{p}p - \overline{n}n\,)\,\pi^0)\,]. \end{aligned} \tag{26}$$

Since the possible values of the isotopic spin for two nucleons is $T = 0, 1$ only, the last interaction, with $|\Delta T| = 2$, is not operative in our approach.

The effective P odd, T odd proton – neutron interaction is derived in the same way as in the AM problem. In the momentum representation it looks as follows:

$$W(\mathbf{q}) \;=\; \frac{g}{2m_p}\,\frac{i\mathbf{q}}{m_\pi^2 + \mathbf{q}^2}\,[\,(\,3g_0 - g_1\,)\,\boldsymbol{\sigma}_p \;-\; (\,3g_0 + g_1\,)\,\boldsymbol{\sigma}_n\,]. \tag{27}$$

In the coordinate representation it is

$$W(\mathbf{r}) \;=\; \frac{g}{8\pi m_p}\,[\,(\,3g_0 - g_1\,)\,\boldsymbol{\sigma}_p \;-\; (\,3g_0 + g_1\,)\,\boldsymbol{\sigma}_n\,]\,\boldsymbol{\nabla}\,\frac{e^{-m_\pi r}}{r}\,. \tag{28}$$

The calculation of the deuteron EDM $\mathbf{d}_d$, i.e., of the $e\mathbf{r}_p = e\mathbf{r}/2$ expectation value, goes along the same lines as that for the anapole moment and results in

$$\mathbf{d} \;=\; -\,\frac{egg_1}{12\pi m_\pi}\,\frac{1+\xi}{(1+2\xi)^2}\,\mathbf{I}. \tag{29}$$

The magnetic quadrupole moment (MQM) operator is expressed through the current density $\mathbf{j}$ as follows (see, for instance, [5, 15]):

$$M_{mn} \;=\; (r_m\varepsilon_{nrs} + r_n\varepsilon_{mrs})r_r j_s. \tag{30}$$

This expression transforms to

$$M_{mn} \;=\; \frac{e}{2m}\left\{3\mu\left[r_m\sigma_n + r_n\sigma_m - \frac{2}{3}\,(\boldsymbol{\sigma}\mathbf{r})\right] + 2q(r_m l_n + r_n l_m)\right\}. \tag{31}$$

Here μ is the total magnetic moment of the particle, q is its charge in the units of e. The magnetic quadrupole moment is the expectation value $\mathcal{M}$ of the operator M_{zz} in the state with the maximum total angular momentum projection $I_z = I$.

In our case, due to the spherical symmetry of the deuteron nonperturbed wave function, the orbital contribution to M_{mn} vanishes. The contact current

generated by the P and T odd charged pion exchange, here is also directed along **r**, and thus does not contribute to MQM. So, the deuteron magnetic quadrupole moment originates from the spin term in (31). It equals

$$\mathcal{M} \,=\, -\,\frac{eg}{12\pi m_p m_\pi}\,\frac{1+\xi}{(1+2\xi)^2}\,[\,(\,3g_0+g_1\,)\,\mu_p+(\,3g_0-g_1\,)\,\mu_n\,)\,]. \qquad (32)$$

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